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Thermal conductivity and viscosity of hybrid nanfluids prepared with magnetic nanodiamond-cobalt oxide ($ND\text{-}Co_3O_4$) nanocomposite

L. Syam Sundar [a,*], G.O. Irurueta [a], E. Venkata Ramana [b], Manoj K. Singh [a,*], A.C.M. Sousa [a]

[a] *TEMA, Department of Mechanical Engineering, University of Aveiro, Portugal*
[b] *I3N, Department of Physics, University of Aveiro, Portugal*

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ABSTRACT

Synthesis of magnetic nanodiamond-cobalt oxide ($ND\text{-}Co_3O_4$) nanocomposite material; preparation of nanofluids and estimation of thermal properties such as thermal conductivity and viscosity has been explained experimentally in this paper. The nanocomposite material has been synthesized by using in-situ growth technique and chemical coprecipitation between cobalt chloride and sodium borohydrate. The various techniques such as XRD, TEM, XPS and VSM have been used to confirm the ND and Co_3O_4 phase of synthesized nanocomposite. The hybrid nanofluids have been prepared by dispersing synthesized $ND\text{-}Co_3O_4$ nanocomposite in water, ethylene glycol/water mixtures. The thermal properties such as thermal conductivity and viscosity have been measured experimentally at different weight concentrations and temperatures. The results reveal that the thermal conductivity enhancements are about 16%, 9%, 14%, 11% and 10% for water, EG, 20:80%, 40:60%, and 60:40% EG/W based nanofluids at 0.15 wt% concentrations and at 60 °C respectively. Similarly the viscosity enhancements are about 1.45-times, 1.46-times, 1.15-times, 1.19-times, and 1.51-times for water, EG, 20:80%, 40:60%, and 60:40% EG/W based nanofluids at 0.15 wt% concentrations and at 60 °C respectively. Based on the experimental data new correlations for thermal conductivity and viscosity have been developed.

1. Introduction

The single phase heat transfer fluids such as water, ethylene glycol (EG), propylene glycol (PG), engine oil (EO) etc are used in many types of industries, such as transportation, air conditioning, power generation, process engineering and electronics. The convective heat transfer of these fluids is very limited, because of low thermal properties. Choi [1] and his team developed a new kind of fluid called as nanofluid and achieved good thermal properties compared to single phase fluids. Nanofluid is defined as dispersion of solid metal or metal oxide particles in nanometer size in single phase fluids. Commonly used nanoparticle for the preparation of nanofluids are Al_2O_3, Ag, CuO, Cu, Co_3O_4, Fe_3O_4, Fe_2O_3, SiC, SiO_2, TiO_2, ZnO, nanodiamond (ND), graphite, and carbon nanotubes (CNT) etc. Masuda et al. [2] observed thermal conductivity enhancement of 33% for A_2O_3/water nanofluid at particle concentration of 4.4%. Lee et al. [3] observed thermal conductivity

* Corresponding authors.
E-mail addresses: sslingala@gmail.com (L.S. Sundar), mksingh@ua.pt (M.K. Singh).

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enhancements of 11% and 19% for Al_2O_3/water and Al_2O_3/EG nanofluid at particle concentration of 4.3% and 5%, respectively. Yiamsawasd et al. [4] obtained thermal conductivity enhancement of 30% for Al_2O_3/20:80% EG/W nanofluid (mass ratio) at volume fraction of 8% in the temperatures between 15 °C and 65 °C. Liu et al. [5] investigated the thermal conductivity of CuO/EG nanofluids without using any surfactant and obtained enhancement of 22.4% at 5 vol%. Yu et al. [6] estimated thermal conductivity of Fe_3O_4/kerosene nanofluid using oleic acid as a surfactant and obtained enhancement of 34.0% for 1.0 vol% nanofluid in the temperature of 10 °C and 60 °C. Mariano et al. [7] estimated thermal conductivity, high pressure density and rheological properties of Co_3O_4/EG nanofluids and obtained thermal conductivity enhancement of 27% at 5.0 wt%. Hosseini et al. [8] prepared a series of ferrofluids were made using oleic acid-capped Co_3O_4 (cobalt oxide) nanoparticles in liquid paraffin by a high-energy milling/sonication method. Hajmohammadi et al. [9] prepared Cu–water and Ag–water nanofluids and studied permeability parameter on skin friction and convection heat transfer coefficient with effects of nanoparticles volume fraction, the type of nanoparticles. Yu et al. [10] estimated thermal conductivity of nanodiamond/EG nanofluid and observed enhancement of 17.23% at 1.0 vol%. Ma et al. [11] observed thermal conductivity enhancement of 73% for ND/water nanofluid at 1.0 vol%. Tyler et al. [12] prepared ND/transformer oil based nanofluid and obtained viscosity enhancement of 80% at 3.0 wt%. Branson et al. [13] prepared ND/EG and ND/mineral oil based nanofluids and found 12% and 11% thermal conductivity enhancements at 0.88% and 1.9 vol%, respectively. Xie et al. [14] prepared ND/55:45% of water and EG mixture based nanofluid and obtained 18% thermal conductivity enhancement with 2.0 vol%. Taha-Tijerina et al. [15] prepared ND/mineral oil nanofluid and obtained thermal conductivity enhancement up to 70% at 100 wt%. The earlier research work explained about the thermal conductivity enhancement of nanofluids with the dispersion of various kinds of single phase nanoparticles. The thermal conductivity enhancement of nanofluids is purely depends on the thermal conductivity of base fluid and single phase nanoparticles. Higher thermal conductivity enhancements of nanofluids are possible by altering the thermal conductivity of nanoparticles, which is possible to make nanocomposite (hybrid) material. Nanocomposites are defined as composite of two or more nanoparticles bonding with each other are also a part of nanoscience and nanotechnology field.

The nanocomposite based (hybrid) nanofluids preparation and its thermal properties are very important in engineering applications. Suresh et al. [16] prepared Al_2O_3–Cu hybrid nanofluids (90 wt% of Al_2O_3 and 10 wt% of CuO) and observed thermal conductivity enhancement of 12.11% at 2.0 vol%. Madhesh et al. [17] prepared Cu–TiO_2 nanofluid and observed heat transfer enhancement 52% at 1.0 vol%. Kumar et al. [18] prepared Zn, Cu and Cu–Zn nanofluids and observed thermal conductivity enhancements of 36%, 42%, 48% and viscosity enhancements of 47%, 53%, 61% at 0.5 vol%, respectively compared to vegetable oil. They also revealed better thermal properties with Cu–Zn nanofluid compared to Zn and Cu nanofluids. Sundar et al. [19] prepared MWCNT–Fe_3O_4 hybrid nanofluid and observed thermal conductivity enhancement of 28.46% at 0.3 vol% at 60 °C. Nine et al. [20] have prepared Al_2O_3-MWCNTs hybrid nanofluids (97.5%-Al_2O_3 and 2.5%-CNT; 90%-Al_2O_3 and 10%-CNT) and studied thermal properties in the weight concentrations of 1–6%. Baby and Ramaprabhu [21] prepared hybrid nanostructures of functionalized MWNT and functionalized HEG (MWNT+HEG) based nanofluids and observed thermal conductivity enhancement of 20% at 0.05% volume concentration. Abbasi et al. [22] synthesized γ-Al_2O_3/MWCNT nanocomposite using a solvothermal process in ethanol and then prepared water based nanofluids using Gum Arabic as a surfactant. Munkhbayar et al. [23] prepared silver/MWCNT hybrid nanofluids by considering 0.05 wt% percentage carbon nanotubes using pulsed wire evaporation instrument. Nine et al. [24] synthesized Cu/Cu_2O water hybrid nanofluid using wet ball milling process by considering accelerates hydrolysis of Cu particles in presence of distilled water. Baby and Ramaprabhu [25–27] synthesized multiwalled carbon nanotubes (MWCNT)/hydrogen exfoliated graphene oxide (HEGO) nanocomposite using catalytic chemical vapor deposition and then prepared hybrid nanofluids. Baby and Ramaprabhu [28] synthesized copper oxide decorated graphene (CuO/HEG) by similar methods and dispersed in water. Paul et al. [29] synthesized Al–Zn nanocomposite using mechanical alloying by considering powders of aluminum (95%) and zinc (5%) and then prepared ethylene glycol based nanofluids. Chen et al. [30] measured effective thermal conductivity of Fe_2O_3–MWNT hybrid nanofluid and showed that the hybrid fillers provide synergistic effect on heat conductive networks. They reported 28% enhancement for thermal conductivity of hybrid nanofluid, which was higher than that of mono nanofluids. Batmunkh et al. [31] measured thermal conductivities of Ag/TiO_2 water nanofluids by using the transient hot wire method with various weight concentrations at temperatures ranging from 15 to 40 °C. Researchers are obtained better thermal properties with nanocomposite material dispersed in various base fluids.

Among all the nanocomposite materials, one can have the interest to select the materials for the synthesis of nanocomposite material for wide variety of applications. In general, magnetic nanoparticles such as Fe_3O_4, Fe_2O_3, Ni and Co_2O_3, Co_3O_4, CoO are widely used in important applications in the field of catalysis [32,33], drug delivery [34], waste water treatment [35], hyperthermia [36], data storage media [37], etc. Among the supported magnetic nanoparticle systems, supported cobalt oxide (Co_3O_4) nanoparticles are interesting due to their applications lithium batteries [38], and in various catalytic reactions [39], aerobic oxidation of alcohols [40], etc. The applicability of nanodiamond (ND) particles in various fields is enormous, because of its high thermal conductivity, high hardness and electrical insulator. Some reports related to ND composites are: Shi et al. [41] synthesized ND/Cu nanocrystals and studied catalytic activity. Voronin et al. [42] have synthesized ND/SiC nanocomposite through mechanical mixing. Nunes et al. [43] have prepared ND/Ni and graphene/Ni nanocomposites through mechanical synthesis. Keeping all the advantages of magnetic material and nanodiamond, a new kind of ND-Co_3O_4 (hybrid) nanocomposite has been synthesized, prepared nanofluids and studied thermal properties for designing heat exchanger devices.

The present paper reveals the synthesis of magnetic ND-Co_3O_4 nanocomposite using simple in-situ and wet chemical reaction method. The nanocomposite used in this study has been satisfies both the high thermal conductivity (ND) and magnetic property (Co_3O_4). The stable hybrid nanocomposite based nanofluids has been prepared by dispersing them in various base fluids and measured both thermal conductivity and viscosity experimentally. These properties are very useful in designing the nanofluids based heat exchange devices. Thermal conductivity and viscosity correlations have been proposed for hybrid nanofluids.

2. Synthesis and preparation of hybrid nanofluids with ND-Co_3O_4 nanocomposite

The chemicals such as cobalt chloride, sodium borohydrate, nitric acid, sulfuric acid, and ethylene glycol were purchased from Sigma Aldrich chemicals, USA. The nanodiamond soot was purchased from International Technology Center, USA with 99% purity and the particle size of 4–5 nm. The purchased nanodiamond soot contains large quantity of carbon impurities. So, it is important to remove the carbon impurities and make it into single nanodiamond particles for the synthesis of nanocomposite. Shi et al. [13] procedure is used to remove the carbon impurities. The procedure follows, purchased DNDs of 5 g were dispersed in 1:3 molar ratios of H_2SO_4 and HNO_3 solution and continued stirring for 72 h and maintain the solution temperature of 60 °C. This method helps to remove the amorphous carbon impurities and the formation of carboxyl groups (COOH) on the surface of the diamond nanoparticles. The solution was washed several times with distilled water and dried in an oven at a temperature of 80 °C for 24 h for obtaining the dry ND particles. Simple technique of in-situ growth and wet chemical reaction method was used to synthesize the nanocomposite material. The acid treated nanodiamond particles were dispersed in 100 ml of distilled water and stirred under magnetic stirring; after that 0.5 g (0.003 M) of $CoCl_2 \cdot 6H_2O$ was added to the solution and continued the stirred up to cobalt chloride is fully dissolved; after that 0.379 g (0.01 M) of $NaBH_4$ was added gradually and observed the formation of light black color precipitate. The precipitate was washed several times with water and dried in an oven at a temperature of 80 °C for 24 h. The bulk quantity of nanocomposite was synthesized based on the above procedure and the pure Co_3O_4 nanoparticles were synthesized without using acid treated nanodiamond particles.

The synthesized ND-Co_3O_4 nanocomposite was characterized by X-ray diffractometry (Siemens D-500), transmission electron microscopy (TEM; JEOL 2200F, 200 kV), vibrating sample magnetometer (Cryogenic, UK) and X-ray photoelectron spectroscopy (SPECS Phoibos 150 spectrometer) and a delay-line detector, using a monochromatic AlKα (1486.74 eV) X-ray source. The nanocomposite based hybrid nanofluids were prepared by dispersing the synthesized ND-Co_3O_4 in water, ethylene glycol, 20:80%, 40:60% and 60:40% EG/W (weight ratio) mixtures. Each nanofluid sample contains 30 ml and prepared in the weight percentages of 0.05, 0.1 and 0.5 by using quantities of 0.015, 0.03 and 0.045 g, respectively. Each nanofluid sample was sonicated in the ultrasonic bath for about 2 h.

3. Results and discussion

3.1. Characterization

The scheme of chemical reaction for the synthesis of ND-Co_3O_4 nanocomposite was shown in Fig. 1a. The nanodiamond-soot was initially treated with strong acid solution for the removal of carbon impurities and the formation of carboxyl groups on the surface of ND particles. The Co_3O_4 nanoparticles were covalent attachment to the surface of ND particles through carboxyl groups. The TEM results for nanodiamond-soot, acid treated ND and ND-Co_3O_4 nanocomposite was shown in Fig. 1b. From the analysis it can clearly observed nanodiamond-soot contain a very thin layer is surrounded by the core nanodiamond particles (Fig. 1b, left), whereas with acid treatment, the carbon layer was removed (Fig. 1b, middle). The formation of ND-Co_3O_4 nancomposite was clearly observed (Fig. 1c, left) and which is identified with different lattice plane distances of ND and Co_3O_4.

Fig. 2 represents the powder XRD of ND, Co_3O_4 and ND-Co_3O_4 nanocomposite. The 2θ position of maximum intense peak for ND for (111) plane is ~43.73°, similarly, the 2θ position of maximum intense peak for Co_3O_4 for (311) plane is ~36.81°, respectively and the final compound ND-Co_3O_4 nanocomposite contains both the phases. All the peaks observed from the pattern corresponds to phase of diamond nanoparticles in agreement with the respective Joint Committee on Powder Diffraction Standards (JCPDS) card no. 00-006-0675 (ND) and 00-042-1467 (Co_3O_4). It is noticed that no additional peaks due to other oxide phases are present, indicating the phase purity of Co_3O_4 nanostructures. However, we observed peak splitting for the planes (111) for diamond nanoparticles and the plane (400) for Co_3O_4 in the specific region (inset); hence, we fitted with the Pseudo-Voigt fitting to the obtained pattern for ND/Co_3O_4 nanocomposite to get the exact 2θ position. The 2θ position for the plane (111) for ND is ~43.73° and for the plane (400) for Co_3O_4 is ~44.85° and also observed the peak broadening.

X-ray photoelectron spectroscopy (XPS) was performed in order to deeply characterize the elemental composition of the surface of the composite as well as the chemical environment of the cobalt, oxygen and carbon atoms. Fig. 3a–c shows high resolution spectra obtained for Co 2p, O 1s and C 1s core levels, respectively. The best fits are also included. Fig. 3a shows the comparison of the Co 2p core level obtained for the cobalt nanoparticles with out nanodiamond (bottom spectrum) and for the composite (upper). Both spectra are very similar indicating that the cobalt particles do not degradates during the process

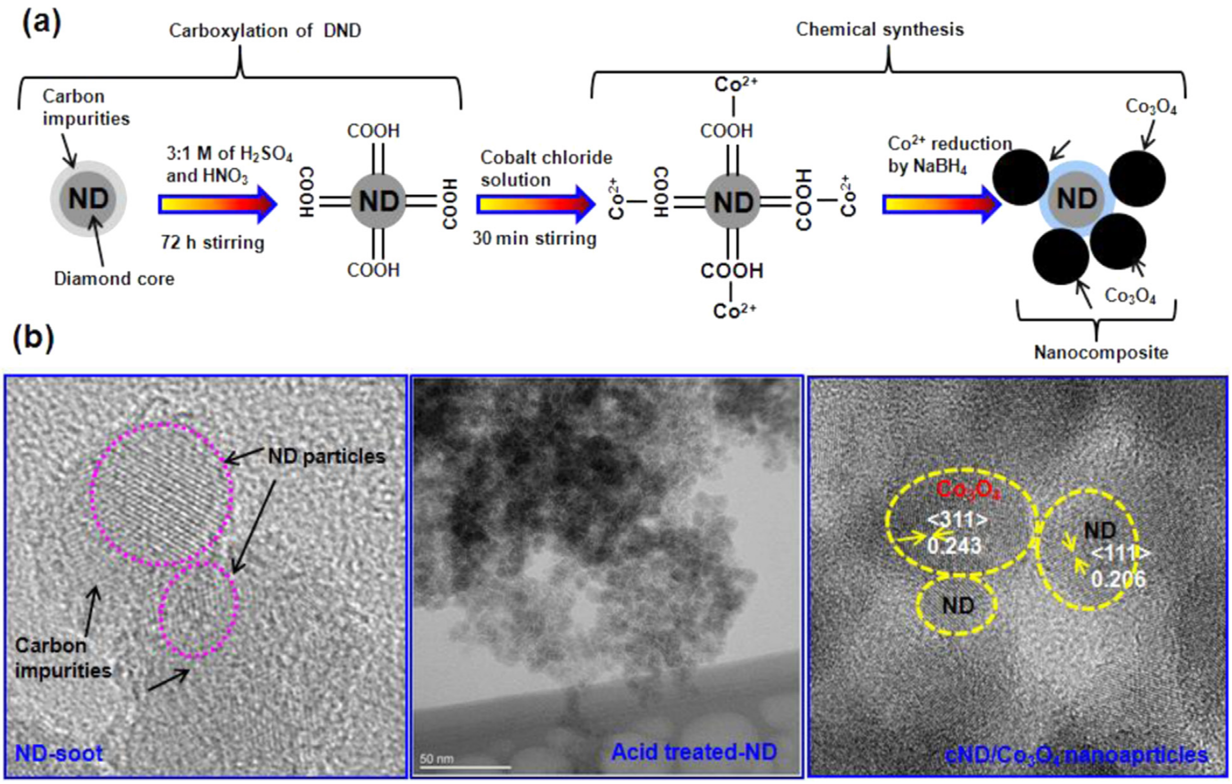

Fig. 1. ND-soot, ND-treated and ND-Co_3O_4 (a) synthesis procedure (b) TEM results (ND-soot; left-side), (ND-treated; middle), (ND-Co_3O_4; right-side).

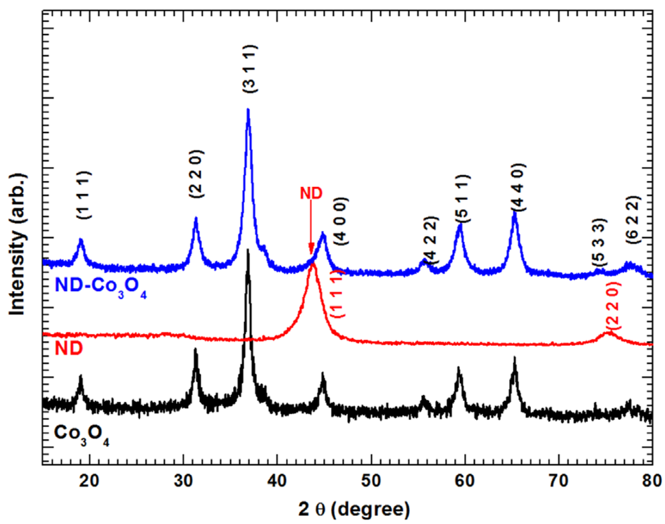

Fig. 2. XRD patterns of ND-treated, Co_3O_4 and ND-Co_3O_4 nanocomposite.

performed for integrating nanodiamonds. Thus, in the following we will focus on the analysis of the composite. Co 2p spectra has two main peaks at binding energies (BEs) of 780.7 and 796.3 eV that can be related with Co $2p_{3/2}$ and Co $2p_{1/2}$ spin orbit lines, respectively. The separation between these two lines is 15.6 eV in good agreement with previous works [44]. It is important to remark that it is rather difficult to determine the oxidation state by considering only the mentioned components. On the contrary, the shape of the satellites and the energy gap between the satellites and the main lines are key parameters used to discriminate between different oxidation states of Co. For instance, the presence of a pronounced satellite like the founded in our sample at 785.7 eV (Fig. 3a) can be adscribed to CoO [45,46]. We notice that in the case of Co_3O_4 compounds the satellite is generally detected at BEs higher than 10 eV with respect to the main peak. Thus, XPS indicates that the Co_3O_4 particles are covered by a thin layer of CoO. The O1s core level is showed in Fig. 3b for the cobalt nanoparticles (bottom) and for the nanocomposite (upper). The first component, centered at a BE=529.5 eV (gray) is adscribed to oxygen atoms in the cobalt particles [44] while the others are related with different oxygen species. In particular, we ascribe the components at 531.6 eV (red) and 533.7 eV (green) with OH^- and C–O/O=C–O, respectively [45]. Moreover, in the case of the nano-composite the C 1s core level (Fig. 3c) shows interesting features. Four components were needed for fitting this peak, appearing at BEs of 284.6 eV (gray), 286.5 eV (red), 287.8 eV (green) and 289.6 eV (blue) that can be adscribed to C–C [46], C–OH or C–O–C [46], C=O [46] and O=C–O [46]. Thus, XPS indicates that the cobalt particles are integrated with the threated nanodiamonds.

To understand the magnetic behavior of synthesized ND-Co_3O_4 nanocomposites its magnetization–magnetic field (*M–H*) hysteresis loops were obtained by using vibrating sample magnetometer (Cryogenic, UK). The magnetic behavior of pure Co_3O_4 nanoparticles was also measured for comparison purpose. Fig. 4 shows the magnetization–magnetic field (*M–H*) hysteresis loops of ND-Co_3O_4 nanocomposite along with pure Co_3O_4 nanoparticles. The results (Fig. 4a) of ND-Co_3O_4 and Co_3O_4 nanoparticles shows hysteresis loop at room temperature (25 °C) due to small particle size and increasing tendency of uncompensated moments at the disordered particles surface resulting from the reduced coordination of the surface spins. That means favorable conditions for ferromagnetic ordering (or spin uncompensation) develop gradually with decrease in

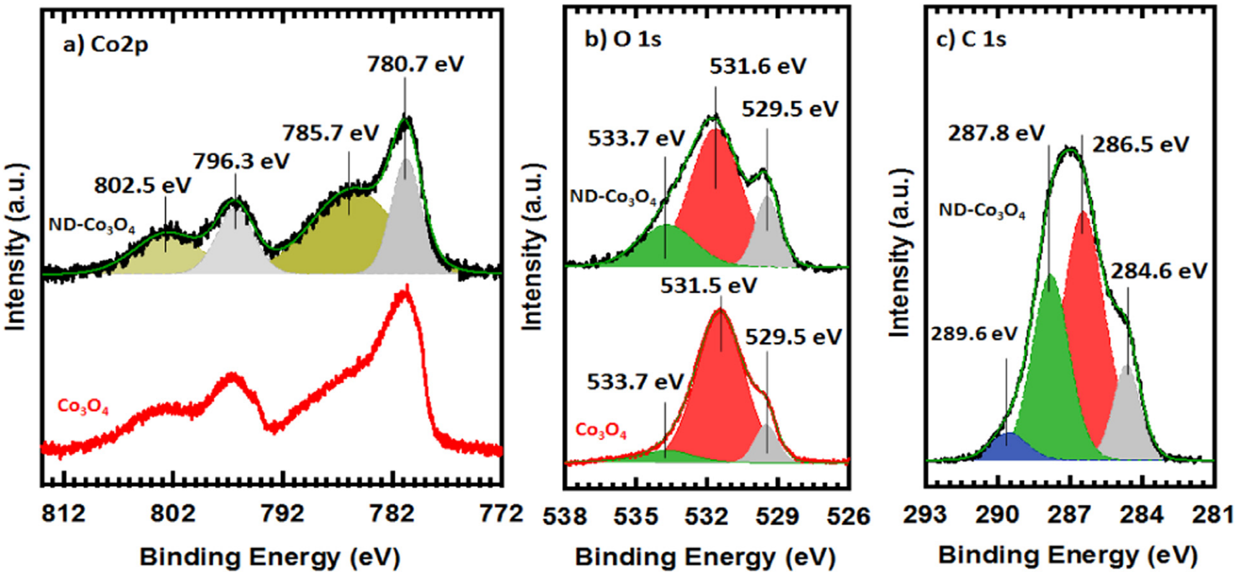

Fig. 3. High resolution XPS spectra (a) Co 2P, (b) O 1s and (b) C 1s core levels for ND-Co_3O_4 and Co_3O_4. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

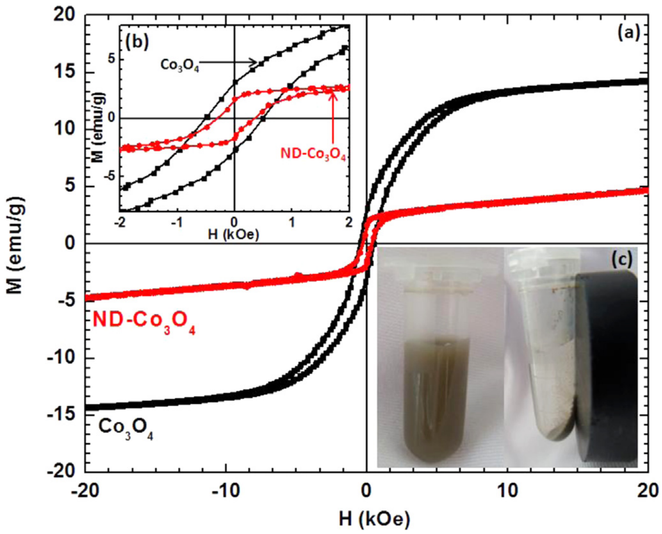

Fig. 4. Magnetic measurement of synthesized Co_3O_4 and ND-Co_3O_4 nanocomposite material. (a) *M–H* curve (b) coercivity (c) the nanocomposite material showing magnetic material while dispersed in water (0.05 wt%).

particle size. The total saturation magnetization of ND-Co_3O_4 nanocomposite is 4.7 emu/g, whereas the pure Co_3O_4 nanoparticle is 14.3 emu/g [47]. The decrease in total magnetization of ND-Co_3O_4 nanocomposite represents the presence of ND particles in the composite. This is caused due to the non-magnetic behavior of ND particles. The coercivity results (Fig. 4b) of ND-Co_3O_4 and of pure Co_3O_4 nanoparticles are 334 Oe and 490 Oe, respectively. In the presence of the magnetic field, the non-magnetic particles act as voids and break the magnetic circuits resulting in the reduction of bulk magnetization with the increase void concentration. The total magnetizations of pure Co_3O_4 are 14.3 emu/g and ND-Co_3O_4 nanocomposite is 4.7 emu/g. The weight percentages of ND and Co_3O_4 materials present in the ND-Co_3O_4 nanocomposite was calculated based on the sum rule of composites and observed as 67% of ND and 33% of Co_3O_4. This result is in consonance with values reported in the literature for assemblies of magnetic/non-magnetic particles [48]. The synthesized ND-Co_3O_4 offering magnetic behavior even though they dispersed uniformly in distilled water. Fig. 4c represents the optical image of separated ND-Co_3O_4 nanoparticles by placing the permanent magnet near the fluid.

3.2. Thermal conductivity of hybrid nanofluids

The KD 2 pro instrument (Decagon Devices, USA) with KS-1 sensor was used to measure the thermal conductivity of nanocomposite nanofluids. The sensor needle measures the thermal conductivity with an accuracy of $\pm 3\%$ in the range of 0.2–2 W/mK. The instrument is calibrated with glycerol and obtained an accuracy of $\pm 2\%$. The thermal conductivity of each nanofluid sample was measured 10 times and the average value is taken as final value. After that, the thermal conductivity base fluids (water, EG, 20:80, 40:60 and 60:40 EG/W) were measured and compared with the ASHRAE hand book data and found a maximum deviation of $\pm 2.5\%$. The water-based nanocomposite hybrid nanofluids were shown in Fig. 5b. The particle size distribution of ND/Co_3O_4 dispersed in water and the zeta potential was measured from Zetasizer Nano ZS (Malvern instruments, UK) using dynamic light scattering method. It is observed that, the size of the synthesized ND/Co_3O_4 is nearly equal to 16.95 nm (Fig. 5c) and the polydispersity (PDI) index values of 0.415. From the XRD patterns also, the same crystalline size was observed. The zeta potential of 0.15 wt% of water based fluid was measured and observed as -34.6 mV, which indicates the nanofluid is in good stability conditions. The size controlled synthesis of nanocomposite material is difficult during the in-situ growth technique; because there may be possibility of achieving the composite size greater than 100 nm. The correct stoichiometric ratio between the cobalt chloride and sodium borohydrate (3:1 M) for obtaining the reaction was used in this study and finally obtained the nanocomposite size less than 50 nm. The thermal conductivity data of water–ND-Co_3O_4 nanocomposite based nanofluids are shown in Fig. 5a. The thermal conductivity of nanofluids increases with increase of particle weight concentrations and temperatures. The nanofluid of 0.05% weight concentration, the thermal conductivity enhancement is about 2% and 6% in the temperatures of 20 °C and 60 °C respectively compared to base fluid (water). In the similarly way, the nanofluid of 0.15% weight concentration, the thermal conductivity enhancement is about 8.7% and 15.7% in the temperatures of 20 °C and 60 °C, respectively compared to base fluid. It is noticed that, thermal conductivity enhancements are lesser at low particle concentrations i.e. 0.05% (weight) and temperatures i.e. 20 °C, and it is higher at high particle concentrations i.e. 0.15% (weight) and temperatures i.e. 60 °C. This difference of enhancements is possible with the micro-convection between the water molecules and hybrid nanoparticles when the temperature of the nanofluid increases. Similar trend of increase in thermal conductivity with the increase in temperature was observed previously by other authors [9–13]. The thermal conductivity data of ethylene glycol-ND-Co_3O_4 nanocomposite based hybrid nanofluids are shown in Fig. 6. The nanofluid of 0.05% weight concentration, the thermal conductivity enhancement is about 1.16% and 3.97% in the temperatures of 20 °C and 60 °C respectively compared to base fluid (EG). In the similarly way, the

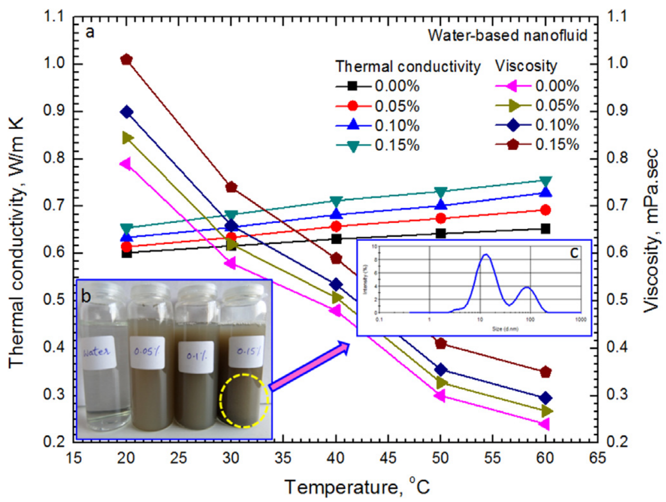

Fig. 5. (a) Thermal conductivity and viscosity of water-based nanocomposite nanofluids (b) water-based nanocomposite nanofluid (c) particle size distribution at 0.15 wt%.

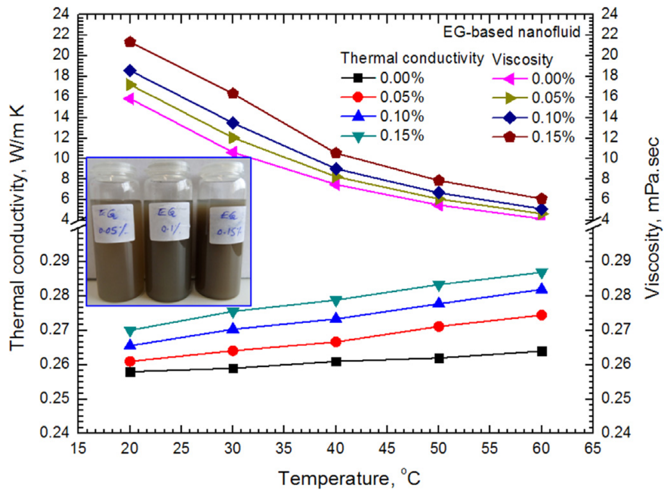

Fig. 6. Thermal conductivity and viscosity of EG-based nanocomposite nanofluids and EG-based nanocomposite nanofluids (inset).

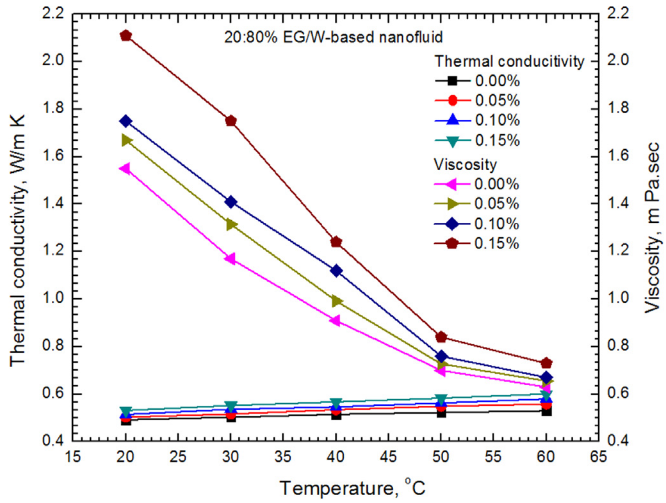

Fig. 7. Thermal conductivity and viscosity of 20:80% EG/W-based nanocomposite nanofluids.

nanofluid of 0.15% weight concentration, the thermal conductivity enhancement is about 4.68% and 8.71% in the temperatures of 20 °C and 60 °C, respectively compared to base fluid. In the present analysis the KD 2 pro instrument is used to measure the thermal conductivity of nanofluids. Generally, the effect of nanoparticles in the base fluids has been usually investigated in regular conductive systems. There are many investigations for nanofluids in non-regular convective configurations for the heat transfer enhancement. Hajmohammadi et al. [49] developed a new technique to enhance the heat transfer from a discretely heated pipe to a developing laminar fluid flow. In general, the fluid is continuously heated along the pipe wall with uniform heat flux, but they considered the heating of fluid with stepwise distributed heat flux and observed heat transfer augmentation. Hajmohammadi et al. [50] also evaluated the architecture of high conductivity pathways embedded into a heat generating body on the basis of Constructal theory. Hajmohammadi et al. [51] explained the non-uniform distribution of heat flux used as a wall boundary condition exerts on the heat transfer improvement in a round pipe. The non-uniform heat flux distribution method also important for aching better heat transfer enhancements [52,53]. The heat transfer enhancement is possible with the thermal conductivity enhancement of the fluids [54]. The thermal conductivity of nanofluids with effect of base fluids was clearly observed from the above analysis. The thermal conductivity enhancement ratio is not constant for water and ethylene glycol base fluids. So the selection of base fluid is also important for obtaining higher thermal conductivity ratios.

The further thermal conductivity of nanofluids was estimated by adding different weight concentration of ethylene glycol in water and obtained data is given below. The thermal conductivity data of 20:80% EG/W-ND-Co_3O_4 nanocomposite based hybrid nanofluids are shown in Fig. 7. The nanofluid of 0.05% weight concentration, the thermal conductivity enhancement is about 2.31% and 5.45% in the temperatures of 20 °C and 60 °C respectively compared to base fluid (20:80% EG/

W). In the similarly way, the nanofluid of 0.15% weight concentration, the thermal conductivity enhancement is about 7.96% and 13.4% in the temperatures of 20 °C and 60 °C, respectively compared to base fluid. The thermal conductivity data 40:60% EG/W-ND-Co_3O_4 nanocomposite based hybrid nanofluids are shown in Fig. 8. The nanofluid of 0.05% weight concentration, the thermal conductivity enhancement is about 2.12% and 3.53% in the temperatures of 20 °C and 60 °C respectively compared to base fluid (40:60% EG/W). In the similarly way, the nanofluid of 0.15% weight concentration, the thermal conductivity enhancement is about 7% and 11.3% in the temperatures of 20 °C and 60 °C, respectively compared to base fluid. The thermal conductivity data 60:40% EG/W-ND-Co_3O_4 nanocomposite based hybrid nanofluids are shown in Fig. 9. The nanofluid of 0.05% weight concentration, the thermal conductivity enhancement is about 2% and 3.2% in the temperatures of 20 °C and 60 °C respectively compared to base fluid (60:40% EG/W). In the similarly way, the nanofluid of 0.15% weight concentration, the thermal conductivity enhancement is about 6.79% and 10.1% in the temperatures of 20 °C and 60 °C, respectively compared to base fluid. The enhancement in thermal conductivity for all the hybrid nanofluids is not constant it varies from one base fluid to other base fluid. The thermal conductivity of hybrid nanofluids prepared with water offering more enhancement compared to other ethylene glycol and ethylene glycol–water mixtures. For all the nanofluids, the thermal conductivity increment is linear with respect to particle loadings and temperatures.

3.3. Viscosity of hybrid nanofluids

The A&D vibro-viscometer (SV-10, Japan) was used to measure the viscosity of nanocomposite nanofluids in the temperature range between 20 and 60 °C. The viscosity data of water–ND-Co_3O_4 nanocomposite nanofluids were shown in Fig. 5a. The nanofluid of 0.05% weight concentration, the viscosity enhancement is about 1.06-times and 1.11-times in the

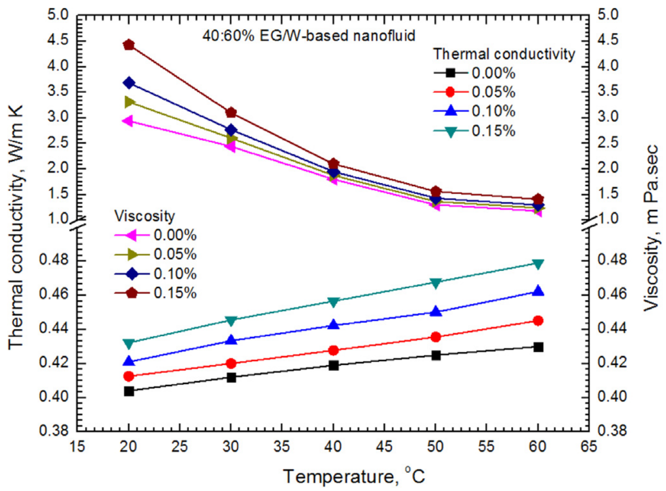

Fig. 8. Thermal conductivity and viscosity of 40:60% EG/W based nanocomposite nanofluid.

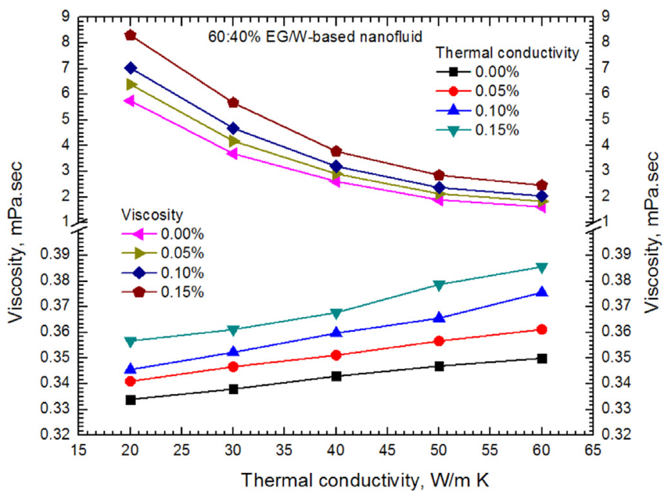

Fig. 9. Thermal conductivity and viscosity of 60:40% EG/W based nanocomposite nanofluid.

temperatures of 20 °C and 60 °C respectively compared to base fluid (water). In the similarly way, the nanofluid of 0.15% weight concentration, the viscosity enhancement is about 1.27-times and 1.45-times in the temperatures of 20 °C and 60 °C, respectively compared to base fluid. It is noticed that, viscosity of nanofluids increases with increase of particle weight concentrations in the base fluid, but decreases with increase of temperature. The viscosity data of ethylene glycol–ND-Co_3O_4 nanocomposite nanofluids were shown in Fig. 6. The nanofluid of 0.05% weight concentration, the viscosity enhancement is about 1.08-times and 1.11-times in the temperatures of 20 °C and 60 °C respectively compared to base fluid (EG). In the similarly way, the nanofluid of 0.15% weight concentration, the viscosity enhancement is about 1.34-times and 1.46-times in the temperatures of 20 °C and 60 °C, respectively compared to base fluid. The viscosity enhancement is not constant for water and ethylene glycol based nanofluids. Ethylene glycol based nanofluids offering more viscosity enhancement compared to water based nanofluids. The viscosity analysis is extended further for different weight ratios of ethylene glycol–water mixture based nanofluid.

The viscosity data of 20:80% EG/W-ND-Co_3O_4 nanocomposite nanofluids were shown in Fig. 7. The nanofluid of 0.05% weight concentration, the viscosity enhancement is about 1.07-times and 1.03-times in the temperatures of 20 °C and 60 °C respectively compared to base fluid (20:80% EG/W). In the similarly way, the nanofluid of 0.15% weight concentration, the viscosity enhancement is about 1.36-times and 1.15-times in the temperatures of 20 °C and 60 °C, respectively compared to base fluid. The obtained viscosity of 40:60% EG/W-ND-Co_3O_4 nanocomposite nanofluids were shown in Fig. 8. The nanofluid of 0.05% weight concentration, the viscosity enhancement is about 1.12-times and 1.04-times in the temperatures of 20 °C and 60 °C respectively compared to base fluid (40:60% EG/W). In the similarly way, the nanofluid of 0.15% weight concentration, the viscosity enhancement is about 1.50-times and 1.19-times in the temperatures of 20 °C and 60 °C, respectively compared to base fluid. The obtained viscosity of 60:40% EG/W-ND-Co_3O_4 nanocomposite nanofluids were shown in Fig. 9. The nanofluid of 0.05% weight concentration, the viscosity enhancement is about 1.11-times and 1.12-times in the temperatures of 20 °C and 60 °C respectively compared to base fluid (60:40% EG/W). In the similarly way, the nanofluid of 0.15% weight concentration, the viscosity enhancement is about 1.44-times and 1.51-times in the temperatures of 20 °C and 60 °C, respectively compared to base fluid. At the same particle concentrations i.e. 0.15%, the observation indicates the following ranking for the thermal conductivity increase is $k_{\mathrm{w}} > k_{20:80\%} > k_{40:60\%} > k_{60:40\%} > k_{\mathrm{EG}}$. Similarly viscosity increase is $\mu_{60:40\%} > \mu_{\mathrm{EG}} > \mu_{\mathrm{w}} > \mu_{40:60\%} > \mu_{20:80\%}$. This difference in thermal conductivity enhancement in different base fluids may be attributable to differences of the thermal boundary resistance around the nanoparticles. In addition, the role of Brownian motion of particles in nanofluids may be an important parameter in determining the thermal conductivity enhancement and also an important factor.

Fig. 10 represents the comparison between the present experimental thermal conductivity of EG-based ND-Co_3O_4 nanofluid and the data of Mariano et al. [7] for Co_3O_4 nanofluids. The thermal conductivity enhancement with increase in temperature was observed in the present case, whereas Mariano et al. [7] observed, decrease in thermal conductivity with increase in temperature. It is worth notice that, the ND-Co_3O_4 hybrid nanofluids offering higher thermal conductivity values compared to pure Co_3O_4 nanofluids in the measured weight concentration range within the same base fluid (EG). So, the nanocomposite materials shows synergistic properties compared single-nanoparticles. Fig. 11 shows the comparison between present experimental viscosity of EG-based ND-Co_3O_4 nanofluid and the data of Mariano et al. [7] for Co_3O_4 nanofluids. The similar trend of increase in viscosity with increase of particle loadings and decrease in viscosity with increase in temperature has been observed by Mariano et al. [7] with Co_3O_4 nanofluid. The order of enhancement is little high in the case of Co_3O_4 nanofluid [7], because they used high particle loadings. In the present study, very small quantities of particle

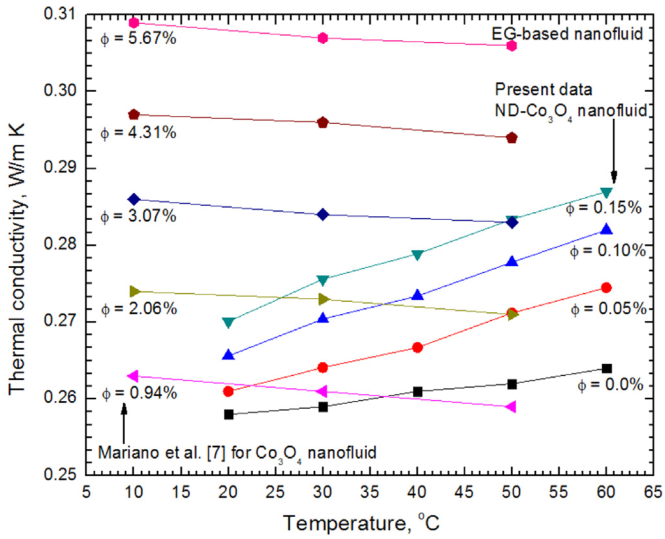

Fig. 10. Comparison of present thermal conductivity data for EG-based ND-Co_3O_4 nanofluid with Mariano et al. [7] data for Co_3O_4 nanofluid.

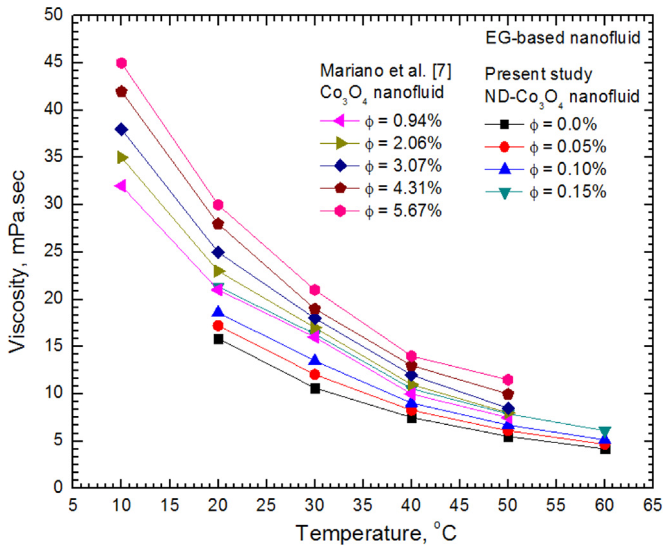

Fig. 11. Comparison of present thermal conductivity data for EG-based ND-Co_3O_4 nanofluid with Mariano et al. [7] data for Co_3O_4 nanofluid.

loadings were used. Present experimental thermal conductivity data for all the nanofluids (75 data points) fitted with an average deviation of 1.43% and standard deviation of 1.85%.

$$\frac{k_{nf}}{k_{bf}}=0.9978(1+\phi)^{0.6556} \tag{1}$$

Present viscosity data (75 data points) for all the nanofluids fitted with an average deviation of 5.37% and standard deviation of 6.69%.

$$\frac{\mu_{nf}}{\mu_{bf}}=0.9595(1+\phi)^{2.399} \tag{2}$$

where ϕ is the weight concentration and the suffixes nf, bf are nanofluid and base fluid, respectively.

4. Conclusion

New kind of magnetic ND-Co_3O_4 nanocomposite was synthesized by in-situ growth and chemical coprecipitation technique and characterized by various techniques. From the magnetic measurement ND-Co_3O_4 nanocomposite shows magnetic property of 3.9 emu/g. The weight percentage of ND and Co_3O_4 presents in the composite was calculated based on the mixture rule and obtained the nanocomposite consists of 16% and ND and 84% of Co_3O_4. The nanocomposite size was measured from DLS method and obtained as 16.95 nm. The stable nanofluids were prepared by dispersing the nanocomposite in water, EG, 20:80, 40:60 and 60:40 EG/W mixtures and estimated thermal conductivity and viscosity experimentally.

The water and EG based hybrid nanofluids prepared with 0.15% weight concentration, the thermal conductivity enhancement is about 15.7% and 8.71% at a temperature of 60 °C. The 20:80%, 40:60% and 60:40% EG/W based hybrid nanofluids prepared with 0.15% weight concentration the thermal conductivity enhancement is about 13.4%, 11.3% and 10.1% respectively at a temperature of 60 °C. The thermal conductivity enhancement with effect of base fluid is clearly observed and the water based nanofluids exhibiting higher thermal conductivity enhancements compared to other base fluids. The viscosity enhancements for 0.15% weight concentration of nanofluid is about 1.45-times, 1.46-times, 1.15-times, 1.19-times and 1.51-times for the base fluids of water, EG, 20:80%, 40:60%, and 60:40% EG/W at a temperature of 60 °C. The viscosity enhancement is more compared to the thermal conductivity enhancement within the measured particle concentrations and temperatures. It is noticed form the analysis the thermal properties of nancomposite based hybrid nanofluids (ND-Co_3O_4) are better than single nanoparticles based nanofluids (Co_3O_4). So, these hybrid nanofluids are future nanofluids for heat exchange devices.

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